January 31, 2024

Performance of a real-time photon counting optical receiver in the presence of emulated channel fading

Free-Space Laser Communications XXXVI

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NASA Glenn Research Center
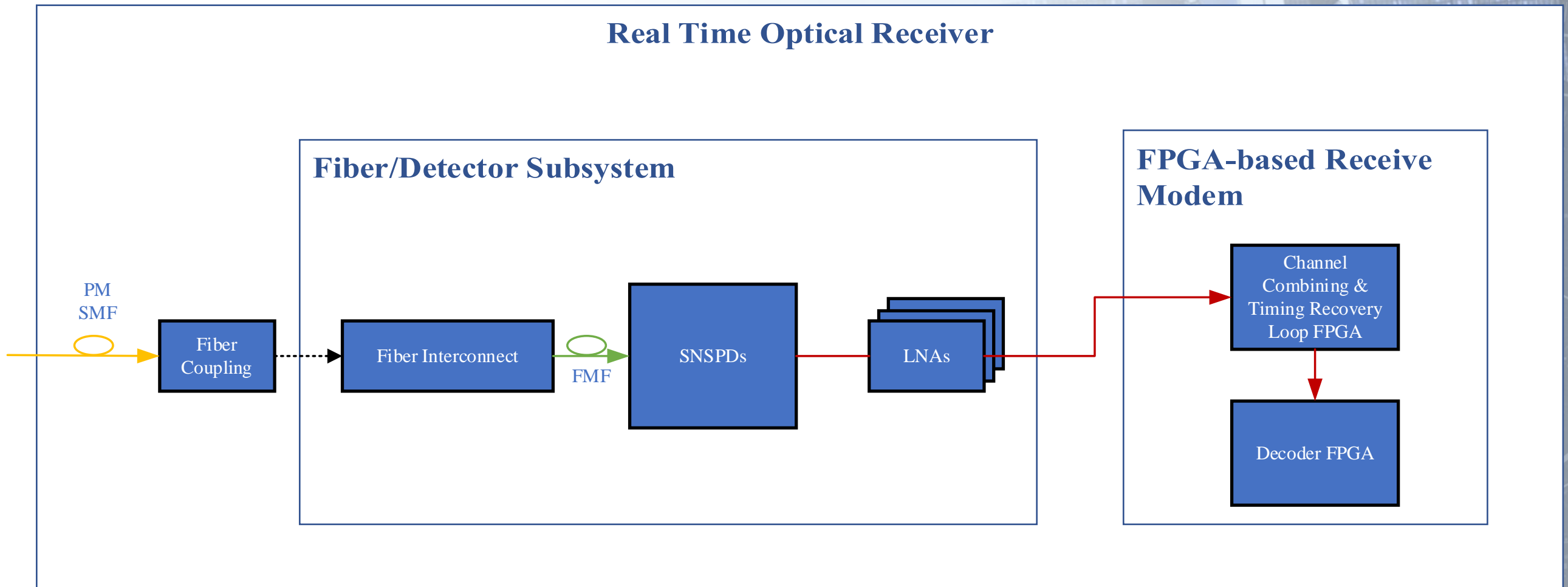
Cleveland, Ohio

Introduction

- **NASA Glenn is building a fiber-coupled photon-counting ground receiver compliant with the CCSDS Optical Communications HPE standard.**

- **Fade emulation testing performed in the presence of emulated fading:**
  - **Atmospheric scintillation**
  - **Beam pointing**
  - **Fiber-coupling**

- **Fades modeled for expected nighttime conditions at NASA Goddard Low Cost Optical Terminal (LCOT) (70 cm telescope)**

- **CCSDS HPE Mode tested:**
  - **PPM-32, Code rate 1/3**
  - **Slot widths: 2 ns, 1 ns, 0.5 ns**
  - **Convolutional channel symbol interleaver with N=84, B = {0, 540, 2160, 4140}**
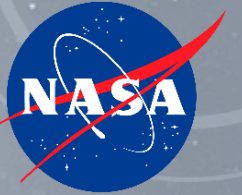
Receiver System
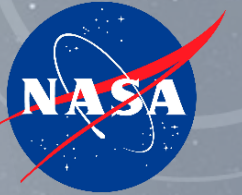
- **Fiber Interconnect**
- **Superconducting nanowire single photon counting detectors (SNSPDs)**
- **FPGA-based receive modem**

Real Time Optical Receiver

Fiber/Detector Subsystem

PM SMF

Fiber Coupling → Fiber Interconnect → FMF → SNSPDs → LNAs

FPGA-based Receive Modem

Channel Combining & Timing Recovery Loop FPGA → Decoder FPGA

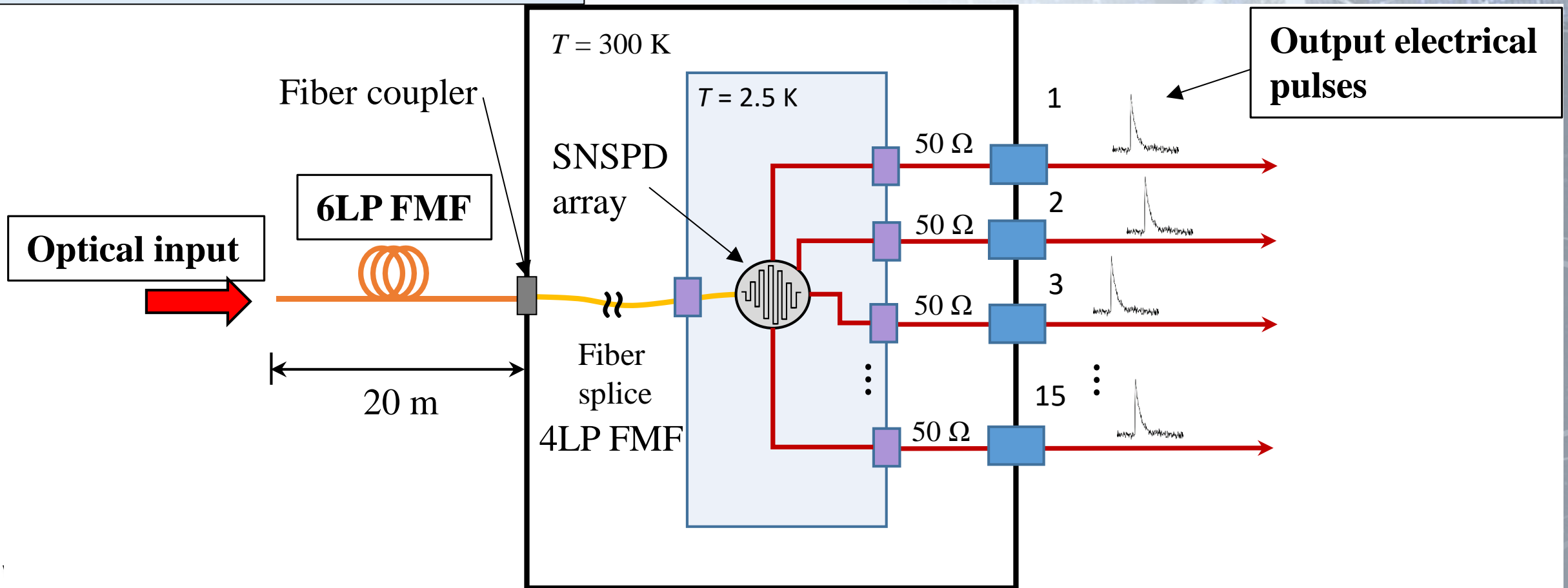# Few Mode Fiber (FMF) and SNSPD Array Architecture
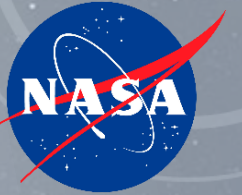
Fiber Interconnect:
- 10-mode, 25 µm, graded index, FMF

Detectors:
- 15-element array
- 1/e reset time: 5-8 ns
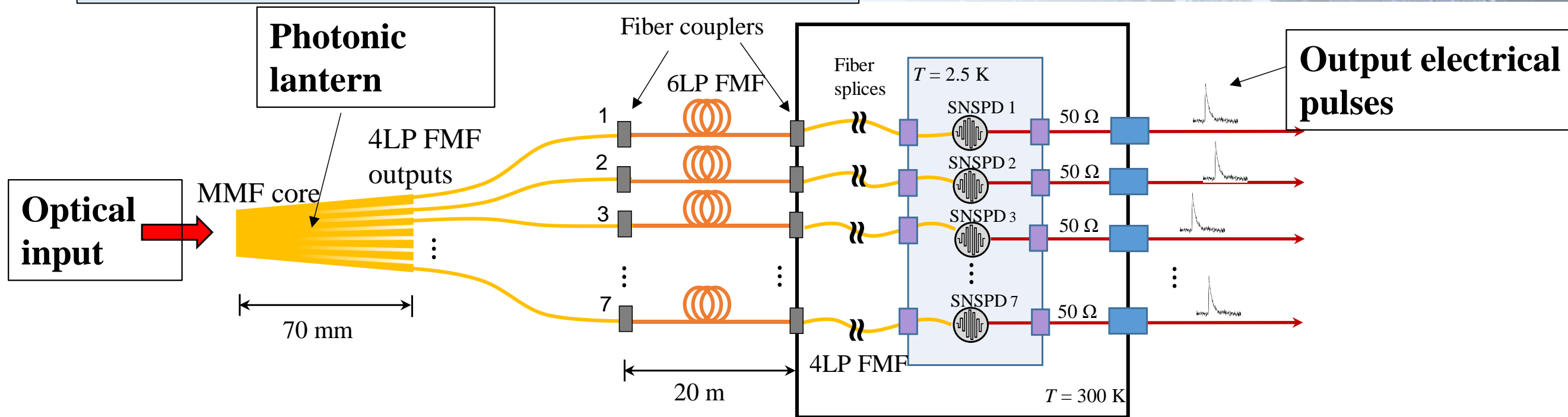
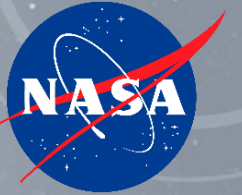# Photonic Lantern and 7 Single Pixel Architecture

Fiber Interconnect:
- Photonic lantern: 70-mode, 55 μm input core, 25 μm, graded index FMF outputs

Detectors:
- 7 single-pixel
- 1/e reset time: 15 ns
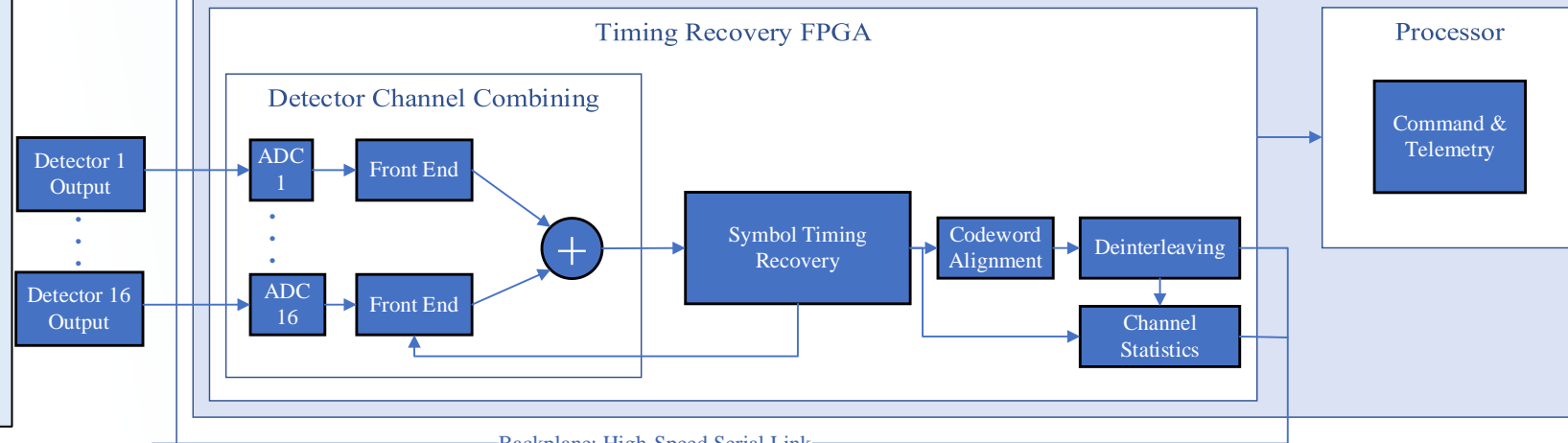
FPGA-based Receiver

Timing Recovery FPGA
- Symbol timing recovery
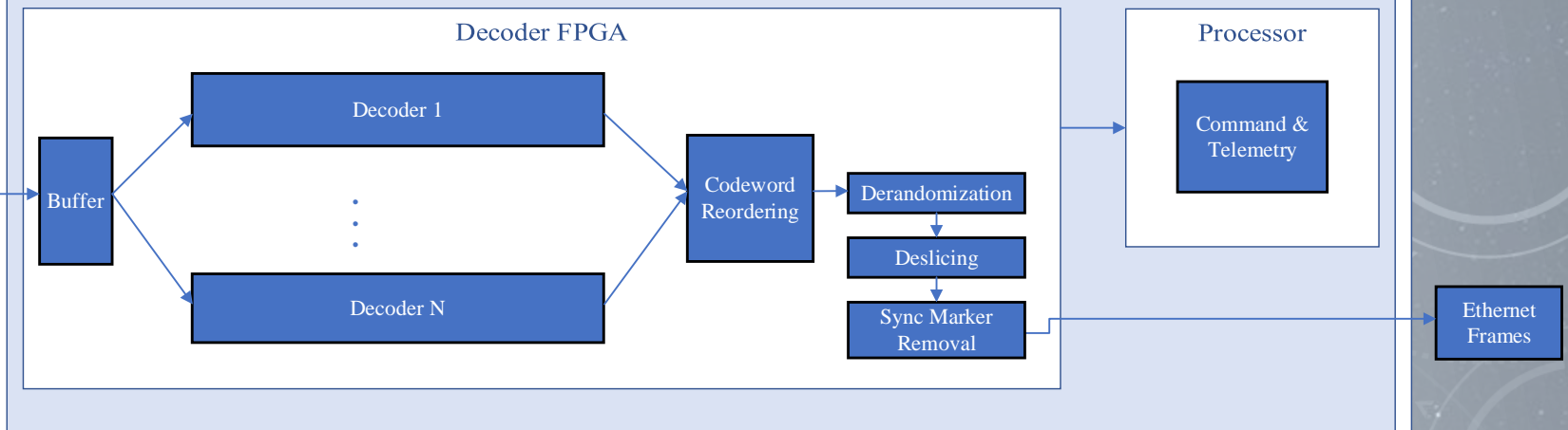- Codeword alignment
- Convolutional deinterleaving

Decoder FPGA
- Iterative decoding
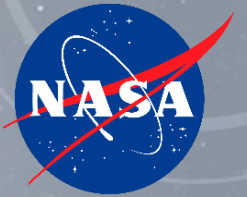- Derandomization
- Deframing

## FPGA-based Receiver: MicroTCA Chassis

Timing Recovery FPGA Card

Timing Recovery FPGA

Detector Channel Combining

Detector 1 Output → ADC 1 → Front End

Detector 16 Output → ADC 16 → Front End

+ → Symbol Timing Recovery → Codeword Alignment → Deinterleaving → Channel Statistics

Processor
Command & Telemetry

Backplane: High-Speed Serial Link

Decoder FPGA Card

Decoder FPGA

Buffer → Decoder 1 ... Decoder N → Codeword Reordering → Derandomization → Deslicing → Sync Marker Removal

Processor
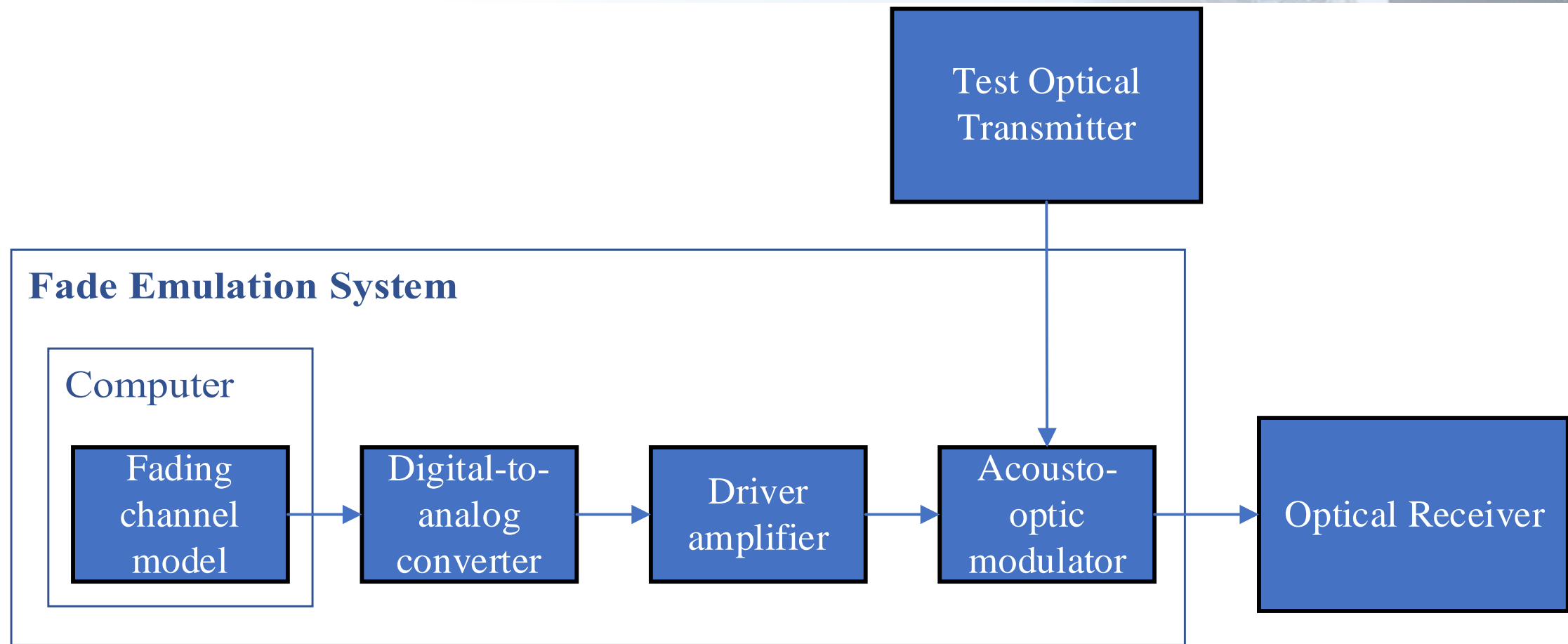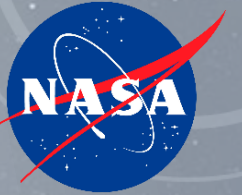Command & Telemetry

Ethernet Frames
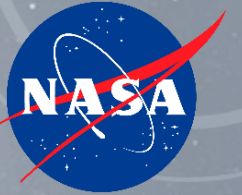
Convolutional Interleaver Background

- A convolutional symbol interleaver is used to mitigate channel fading.

- The interleaver has N rows of length iB, where i is the row number and B defines row length.

- After acquisition, the initial contents of memory must be cleared, which takes $NB(N-1)$ symbol reads.
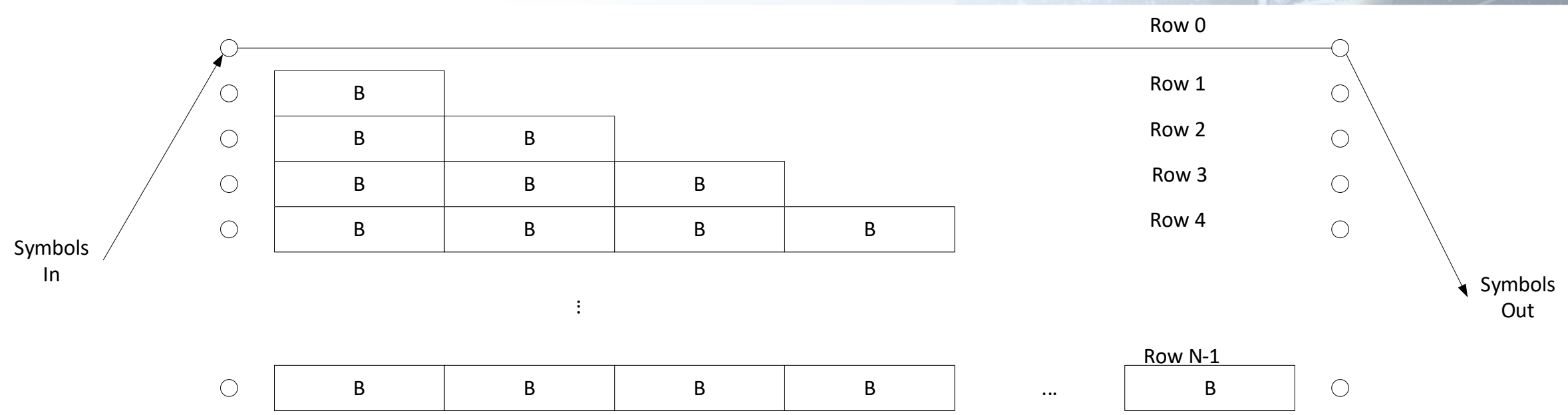
Fade Emulation Test Setup

Channel fade model

- Three sources of channel fade are modeled:
  1. Scintillation-induced fade (**SIF**) from aperture-averaged atmospheric scintillation effects (**log-normal**)
  2. Pointing-induced fade (**PIF**) from transmitter pointing error (**beta distribution**)
  3. Coupling-induced fade (**CIF**) into fiber interconnect from uncorrected wavefront (**Weibull distribution**)

- Scintillation and pointing-induced fade derived from atmospheric model and pointing link budget

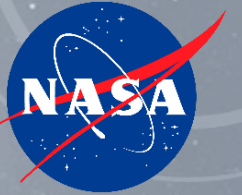| Scint. index σ_I^2	Atm. coherence time τ_c	Pointing jitter β	Pointing jitter cutoff freq. f_c
0.025	1 ms	16	10 Hz

Channel fade model
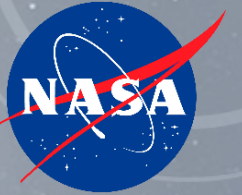
- **Coupling-induced fade depends on fiber/detector architecture and severity of atmospheric turbulence** (D/r_0)

    - Fading PDF largely determined by average coupling efficiency η

- **Measured coupling losses:**

Fiber Interconnect	$D/r_0 = 4$	$D/r_0 = 9$
10-mode fiber	4.8 dB	10.6 dB
70-mode photonic lantern	2.9 dB	5.5 dB

Fade Testing

- CCSDS HPE Mode tested:
  - PPM-32, Code rate 1/3
  - Slot widths: 2 ns, 1 ns, 0.5 ns
  - Convolutional channel symbol interleaver:
    - N=84, B = {0, 540, 2160, 4140}
- The power scintillation index, σ_I^2, atmospheric coherence time, τ_c, and pointing jitter distribution β, were kept constant.
- Two fade scenarios (D/r_0 = 4,9)

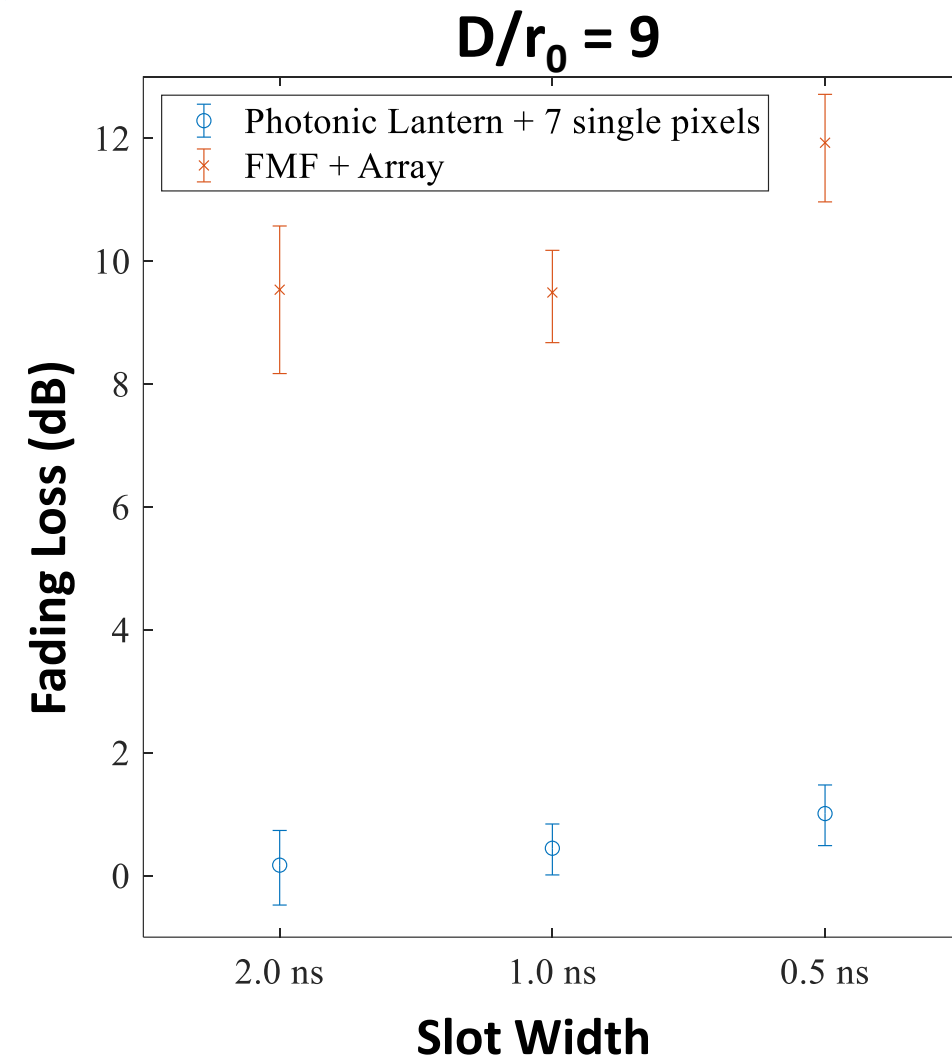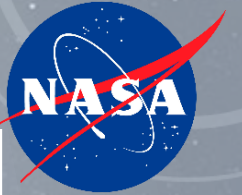| Fade Scenario	Scintillation Index, σ_I^2	Atmospheric Coherence Time, τ_c	Telescope Coherence Ratio, D/r_0	Pointing Jitter Distribution β
1	0.025	1 ms	4	16
2	0.025	1 ms	9	16

Baseline Performance Without Fading
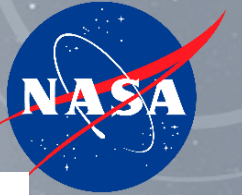
Timing recovery loop acquisition power
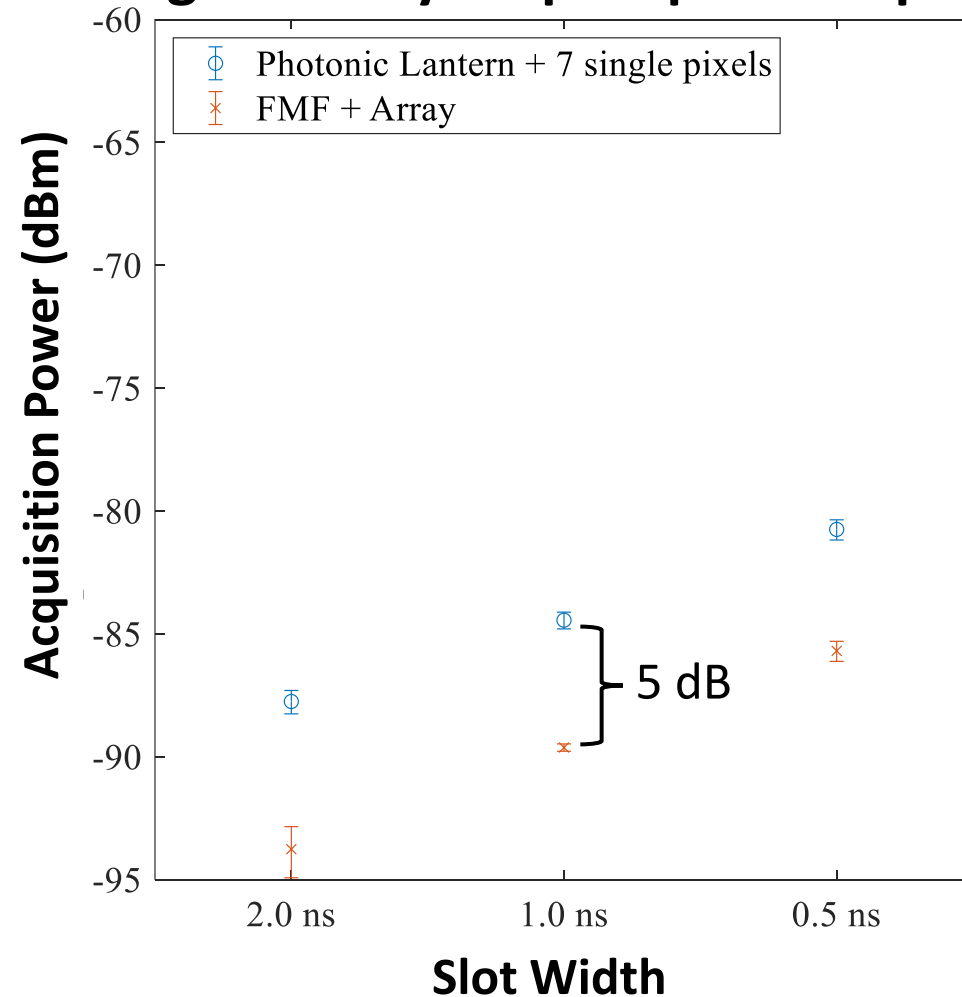
Codeword error rate 10^{-4} power

Photonic lantern and 7 single pixel architecture requires 4-5 dB more power
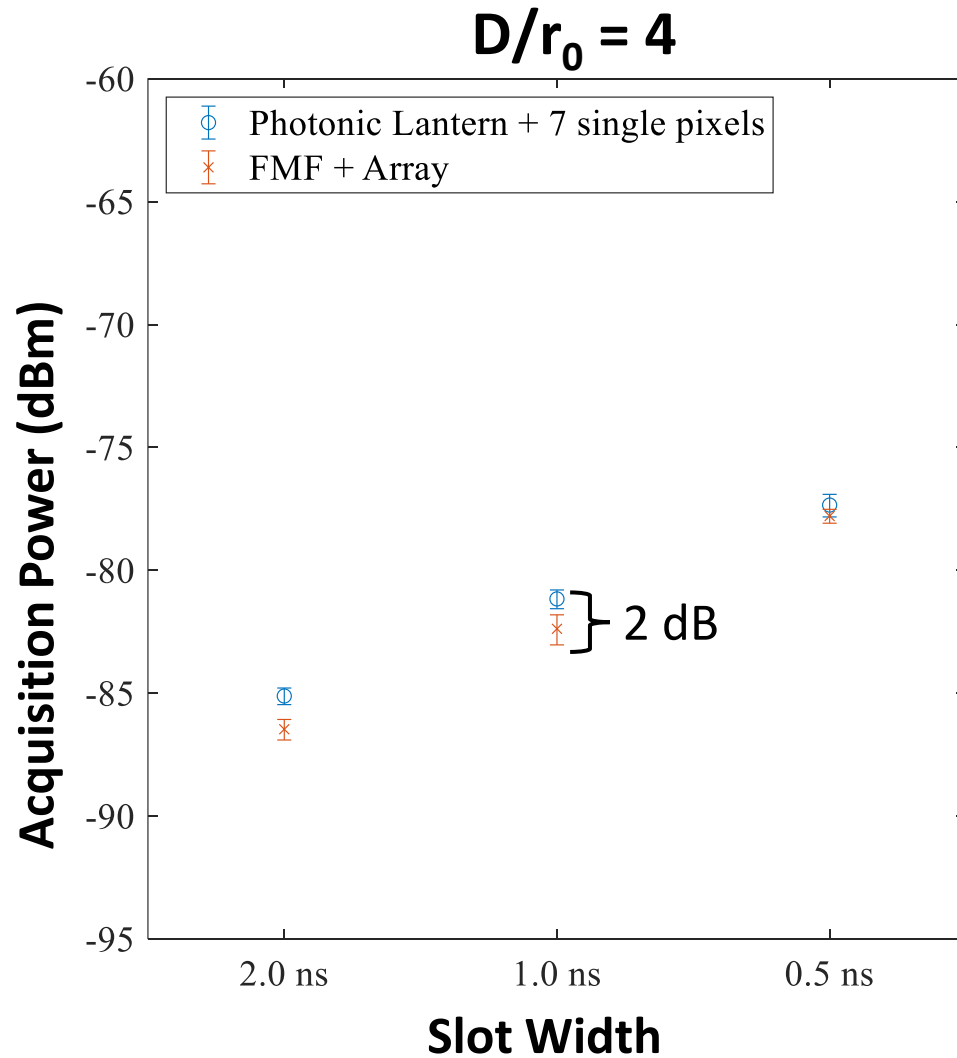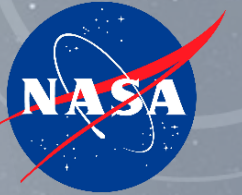
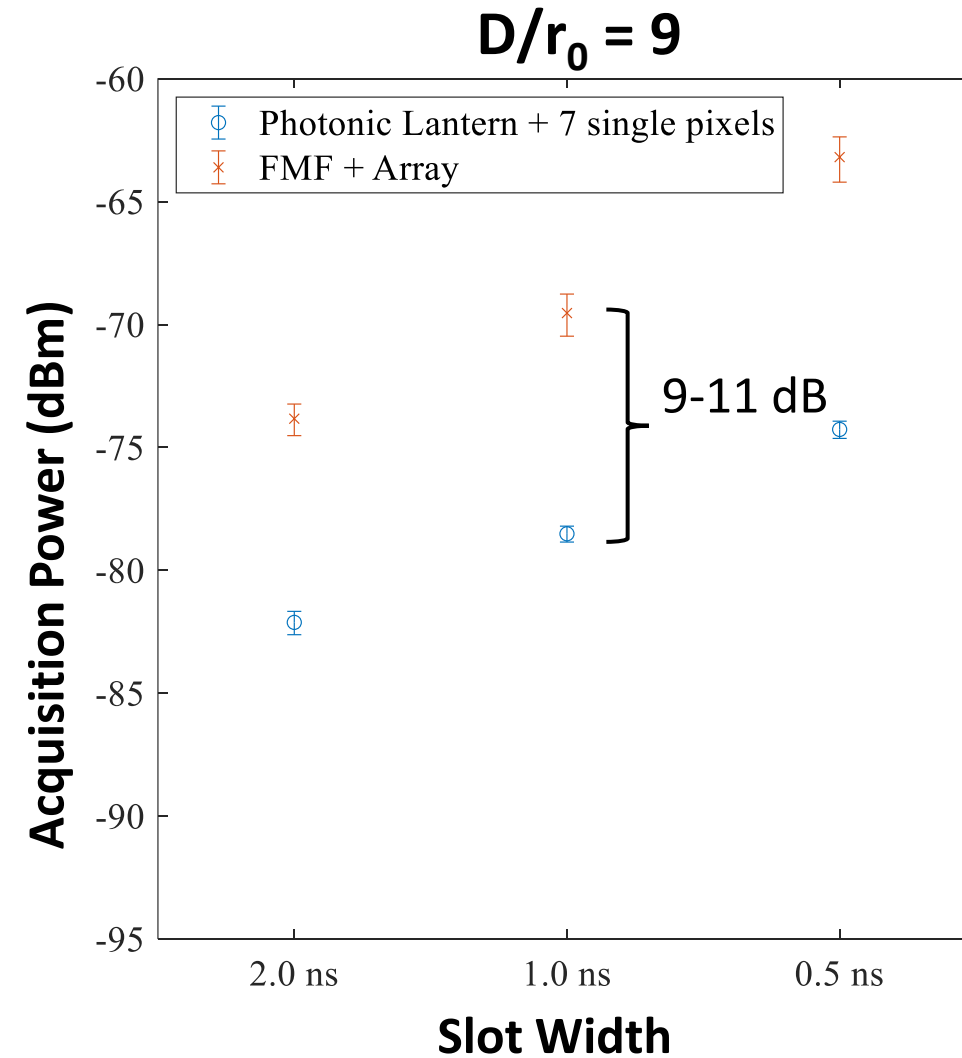# Fading Loss

D/r_0 = 4

D/r_0 = 9
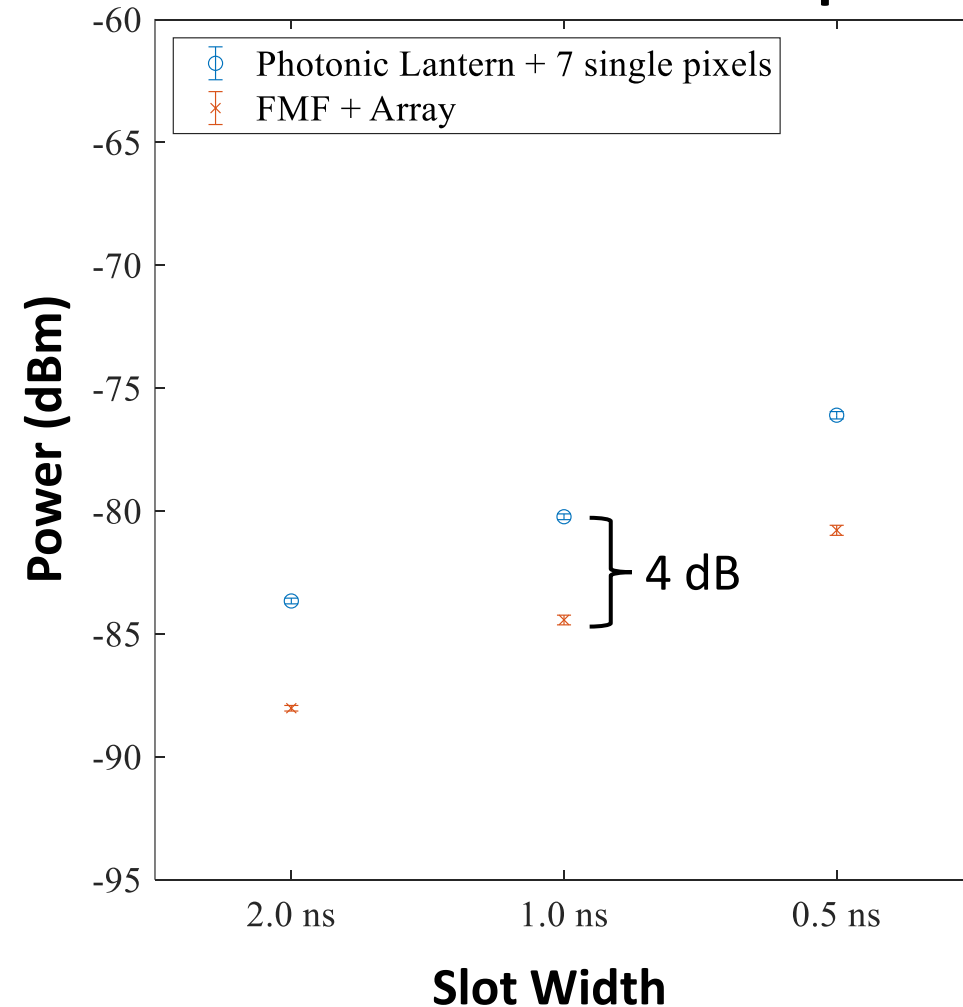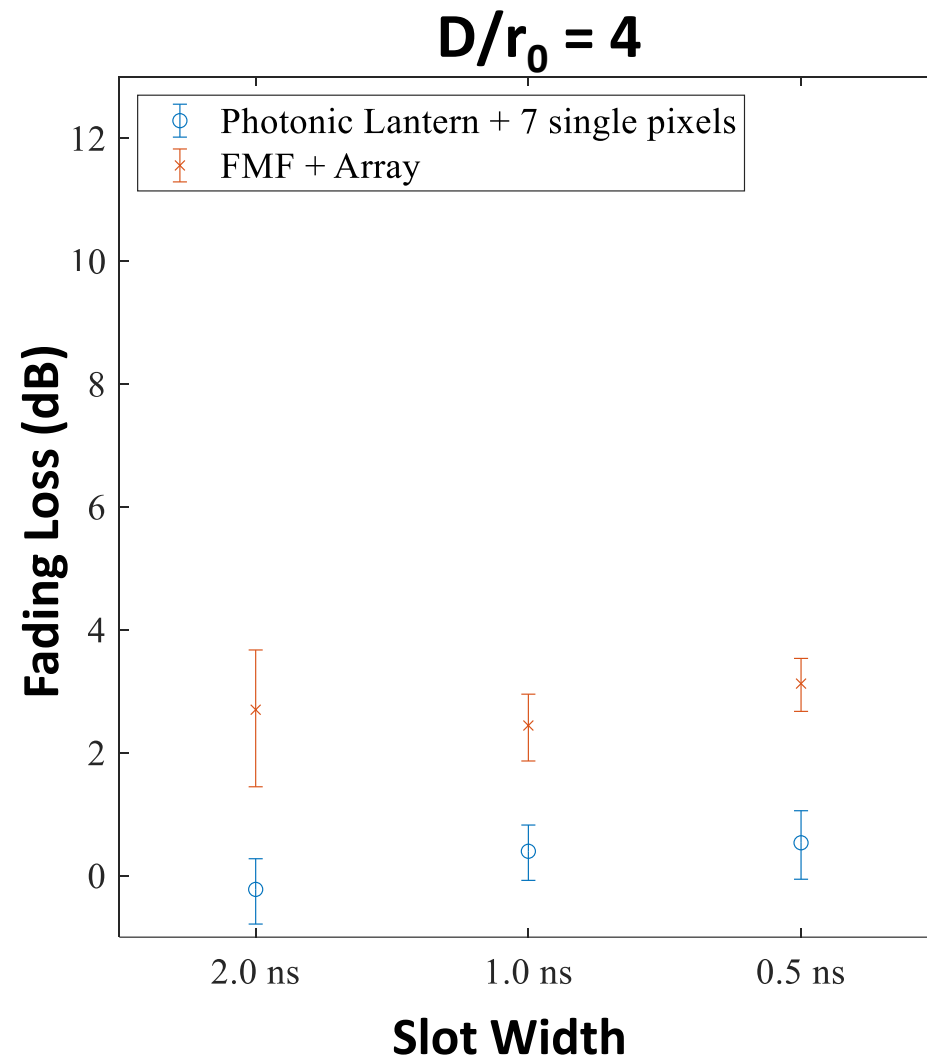
- **Photonic lantern + 7 single pixel has a fading loss 0-1 dB.**
- **FMF + array has a fading loss of 3-4 dB in lower turbulence and 9-12 dB in higher turbulence.**
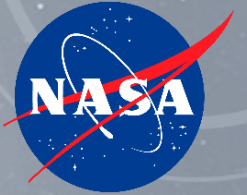
Performance with Fading and Fiber Coupling Loss

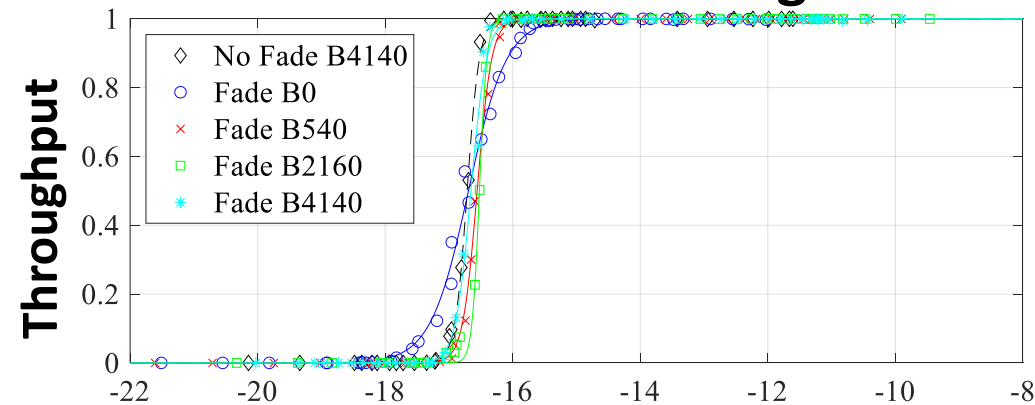D/r$_0$ = 4

D/r$_0$ = 9

Architectures within 2 dB in lower turbulence.

FMF + array requires of 9-11 dB more power in higher turbulence.

Codeword Error Rate and Throughput, 0.5 ns Slot Lower Turbulence, $D/r_0 = 4$
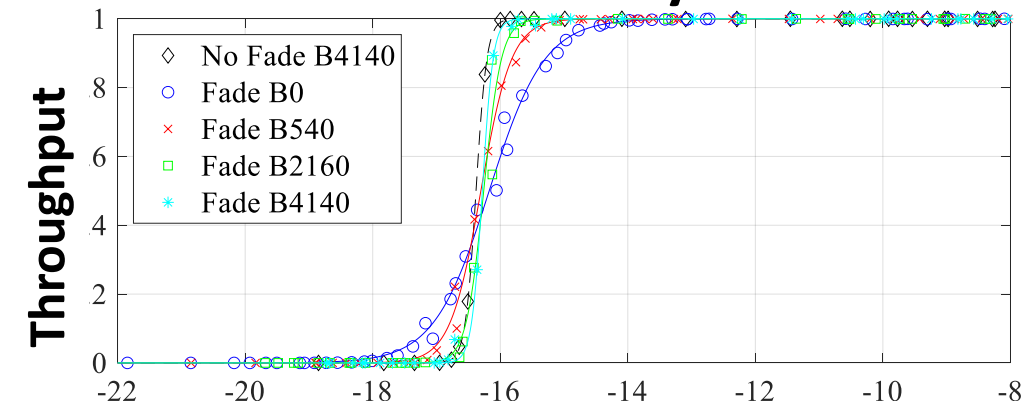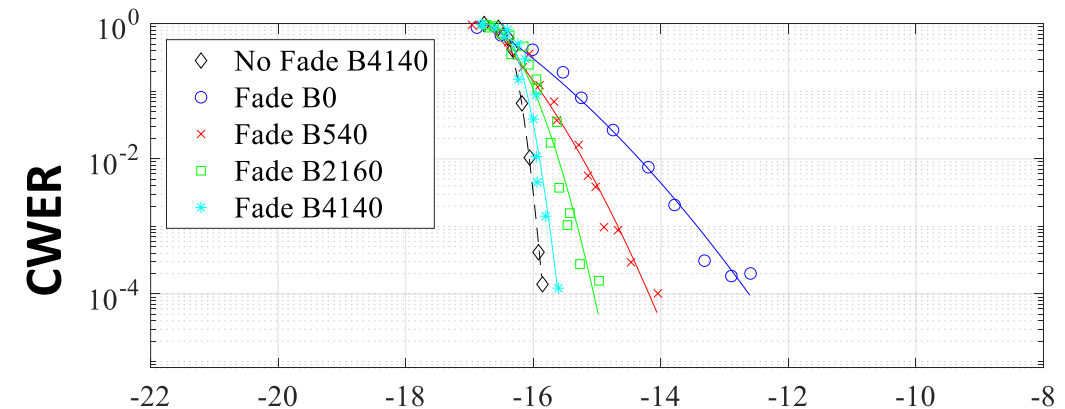
Photonic Lantern + 7 Single Pixels
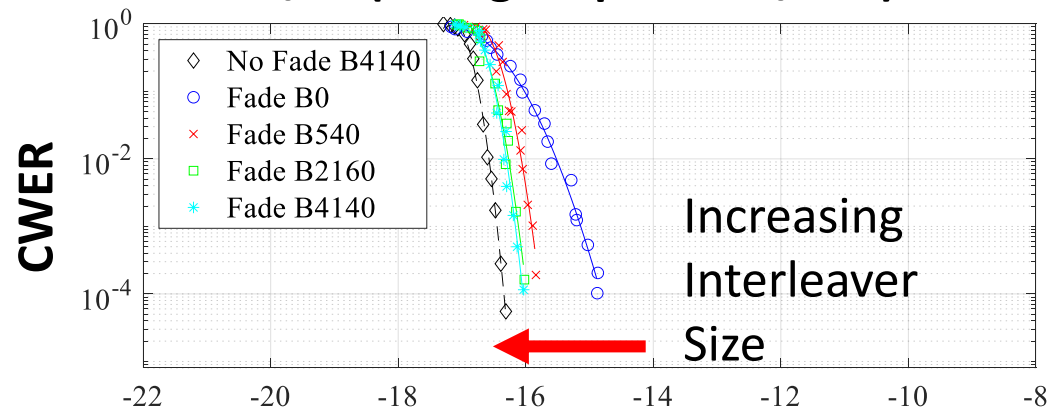
FMF + Array
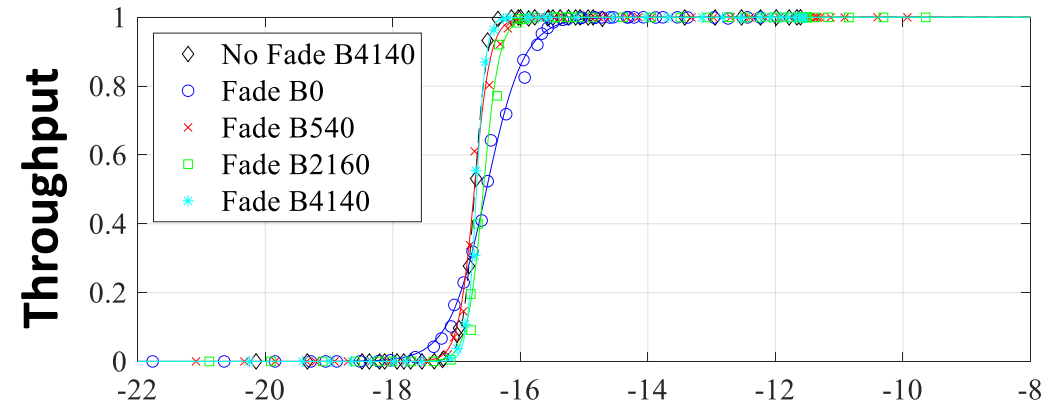

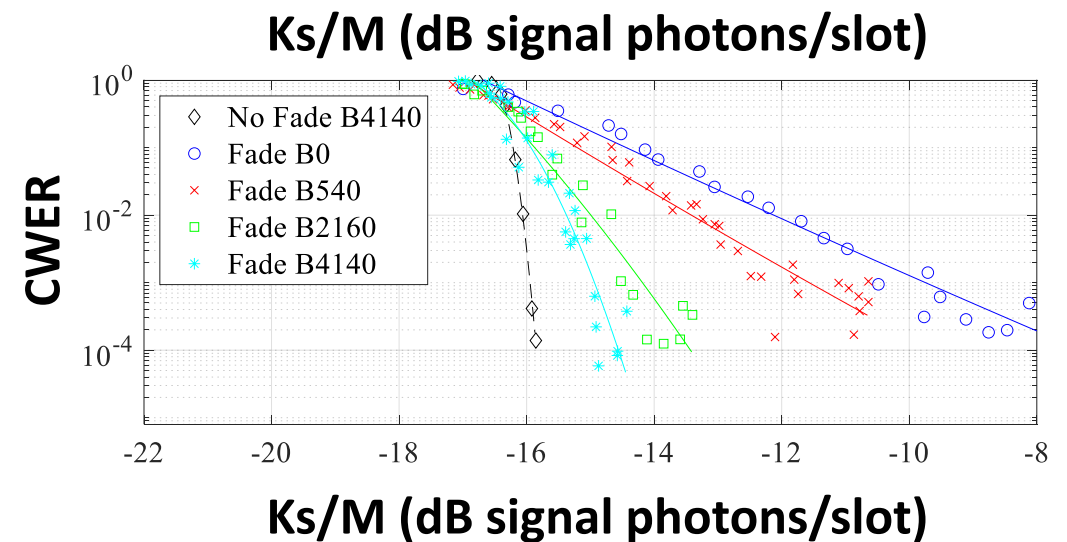**Larger interleaver improves throughput and codeword error rate (CWER).**
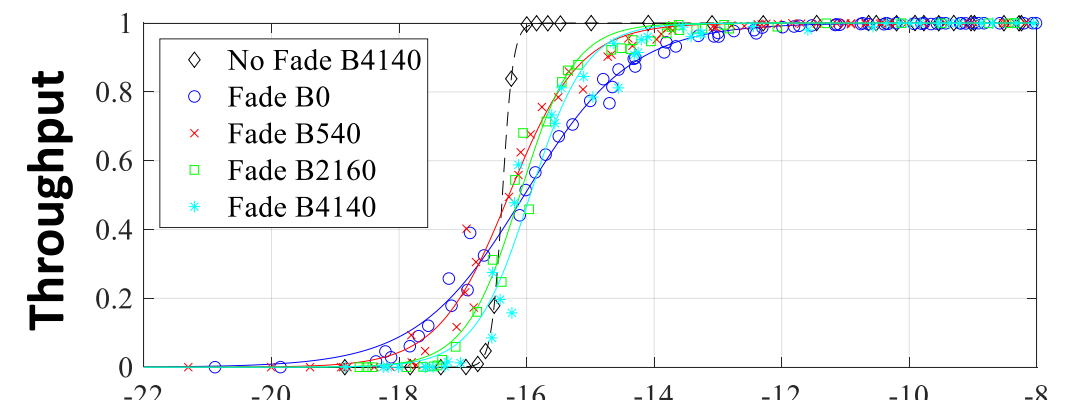
Codeword Error Rate and Throughput , 0.5 ns Slot Higher Turbulence, $D/r_0 = 9$
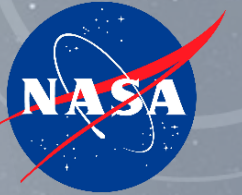
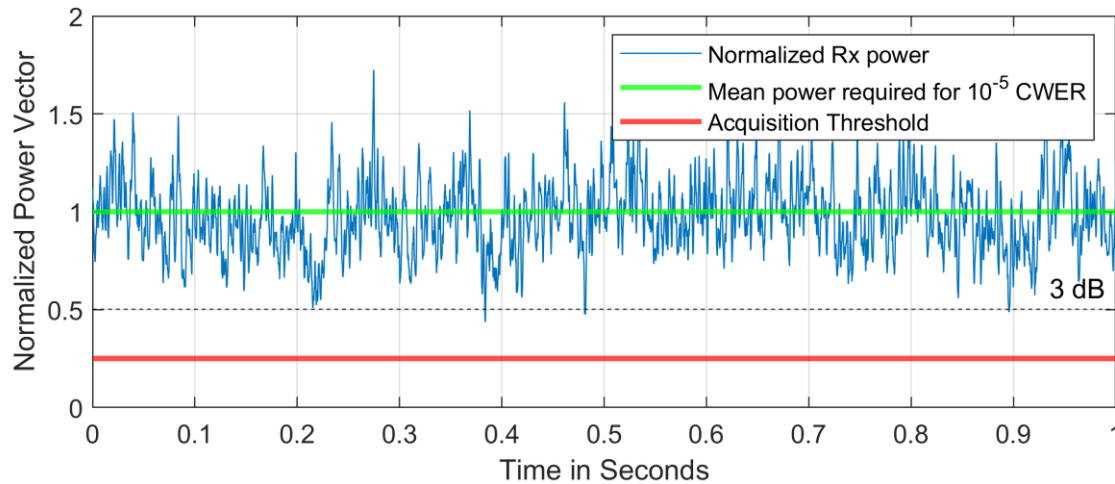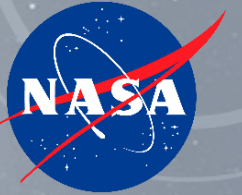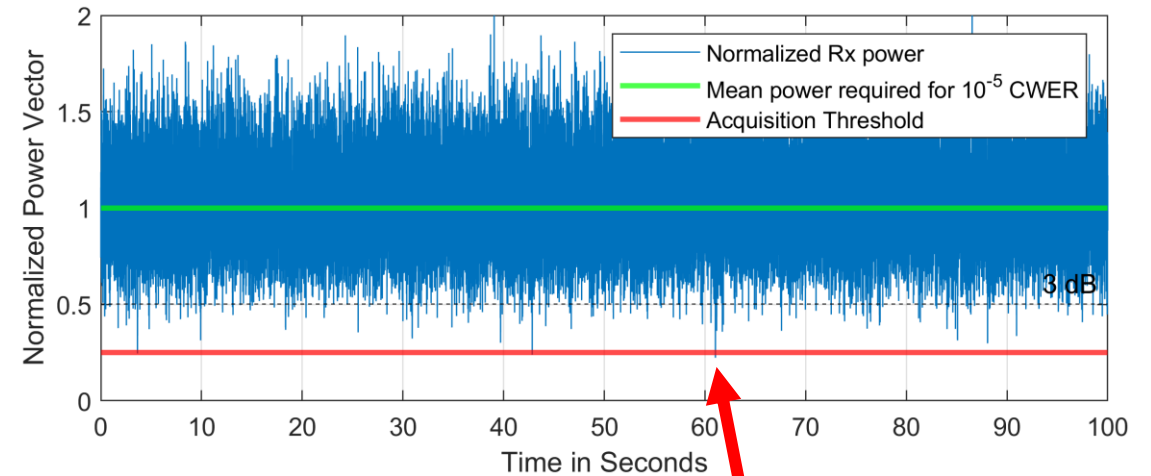## Photonic Lantern + 7 Single Pixels
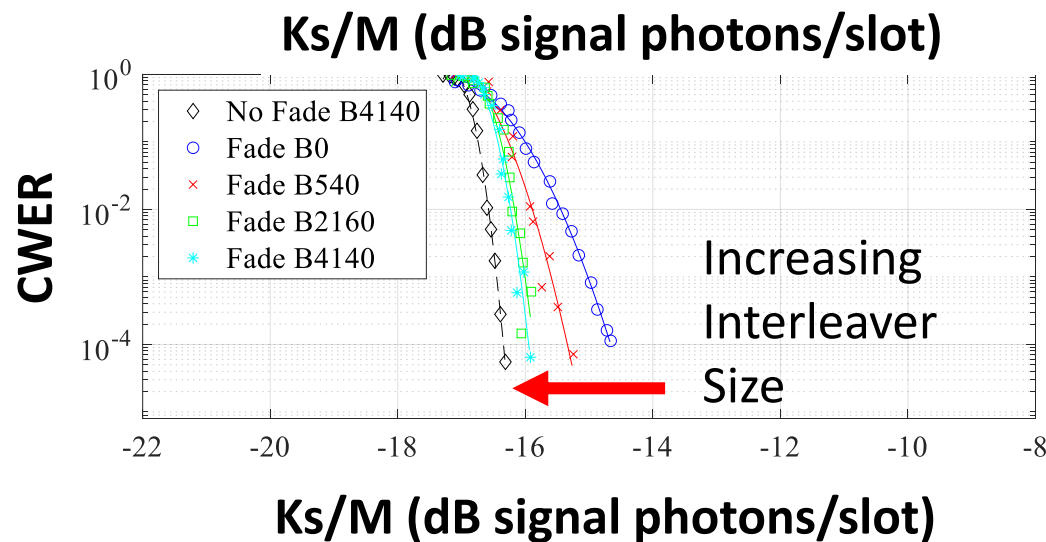
FMF + Array

Throughput is lower for larger interleaver with the FMF + Array architecture.

Channel Fading and Interleaver Size Analysis

- Power remains above acquisition threshold
- Interleaving mitigates fade

- Deep fade below acquisition threshold
- Interleaver flush can take up to ~0.58 seconds (B = 4140, Slot Width = 0.5 ns)

Achieving error free codeword throughput loss requires enough margin above acquisition threshold to include even very rare fades.

Conclusion

- Two architectures for a fiber-coupled photon-counting ground receiver have been developed and tested in the presence of emulated fades.

- FMF + 15-channel array has a 4-5 dB advantage without fades.

- When operating in an optical ground station, such as NASA Goddard LCOT, it is expected that both architectures will perform within 2 dB for lower turbulence ($D/r_0 = 4$).

- At higher turbulence ($D/r_0 = 9$), the photonic lantern + 7 single pixel architecture has a significant advantage: 9-11 dB.

- Convolutional interleaver improves the performance in the presences of fades as long as acquisition is maintained.

Thank You!

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